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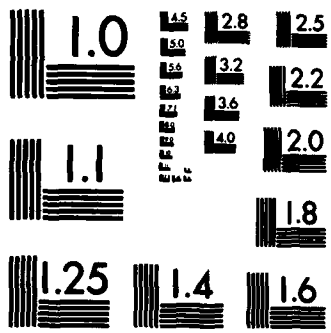
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A study has been made of precipitation hardened alloys because their fatigue properties can be improved by a much smaller factor than their monotonic strengths. The aim of the work has been to understand why the hardening precipitates are unstable to cyclic strain because this leads to cyclic softening in persistent slip bands (PSB's), strain localization and, therefore, fatigue failure at disappointingly low applied stresses. Both crack nucleation and propagation mechanisms are affected by such precipitate instability and PSB's.

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CYCLIC DEFORMATION AND FATIGUE
OF PRECIPITATE HARDENED SINGLE CRYSTALS

Final Report

Campbell Laird

August 1, 1982

U.S. Army Research Office

DAAG-29-78-C-0039

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1. Statement of Problem Studied

Along with corrosion and wear, fatigue is a major factor in limiting the life and performance of both military and civilian hardware, and indeed some types of wear are caused by a fatigue mechanism. In the last twenty years, major developments have taken place in understanding fatigue and in designing against it with resultant savings in lives and material. The greatest emphasis has been placed on studying crack propagation of long cracks but current trends are in the direction of the earlier stages of fatigue life because the greater part of the life is associated with these stages. Understanding the definition and assessment of damage under variable loads is still in a very primitive stage of development.

In the work done under the present grant, a study has been made of precipitation hardened alloys because their fatigue properties can be improved by a much smaller factor than their monotonic strengths. The aim of the work has been to understand why the hardening precipitates are unstable to cyclic strain because this leads to cyclic softening in persistent slip bands (PSB's), strain localization and, therefore, fatigue failure at disappointingly low applied stresses. Both crack nucleation and propagation mechanisms are affected by such precipitate instability and PSB's.

The mechanisms of instability differ in different alloy systems and between commercial and experimental alloys. Thus Al-Zn-Mg alloys soften by precipitate dissolution (1), but Al-Cu alloys do not (2). In the latter system, Calabrese and Laird (2) suggested that the strengths of the shearable precipitates were reduced by

disordering of their crystal structure by cyclic stressing. To check this idea, Al-Ag alloy containing GP zones, which are known to be disordered as formed and in the absence of cycling, was cycled to find out whether or not it underwent cyclic softening (3). It did not, and instead hardened by fatigue-induced precipitation to high flow stresses (3). In order to suppress such precipitation, we proposed to strain-cycle Al-Ag alloy at 78K. Furthermore, to study the localization of strain during fatigue, we proposed to cycle Al-Cu single crystals containing coherent θ'' precipitates and to measure the strain in individual PSB's by interferometry. We particularly wanted to study the changes in strain localization which occur during cyclic softening.

Since cyclic response is used with increasing acceptance as a new approach to studying fatigue under variable loads, the cylic deformation behavior of both monocrystalline and polycrystalline Al-Cu alloy containing shearable θ'' precipitates has also been explored in step tests known to give bounding results in pure metals.

2. Summary of Results

The study of Al-Ag alloy was done first (4). A low temperature strain cycling rig was built and Al-Ag alloy, suitably prepared with GP zones, was cycled at 78K. In support of the disordering hypothesis of cyclic softening, no cyclic softening was observed (4), and the experiment was thus considered valid in support of the disordering hypothesis. However, at the lowest strains studied, with consequent longest lives, fatigue-induced precipitation of γ'/γ precipitates was discovered by TEM (4). We interpreted this astonishing

result on the consideration that vacancies would indeed be immobile at 78K but dislocation interactions would produce interstitial defects and these could cause the diffusion necessary to form the γ'/γ plates (4). Moreover, the γ'/γ plates formed close to pre-existing GP zones (and at their expense) so that the range of the diffusion required would be small.

For the study of Al-Cu single crystals containing θ'' precipitates, we required very accurate control and recording of plastic strain. A new MTS machine was bought, modified and developed (a task which took three months and much bullying of the supplier to meet his own specifications). Even after this, recording strain down to 10^{-6} was inadequate and we therefore built our own system to bypass the MTS electronics. For accurate X-Y recording of the plastic strain at any part of the hysteresis loop, and especially at 0 stress where the anelastic strain is zero, we arranged to chop off the extremities of the loops and thus to limit the travel of the pen. This system has worked very well, and the results at low strains were obtained with it.

Just like polycrystals, Al-Cu single crystals harden to a peak and then cyclically soften. We were delighted to find that the cyclic stress-strain curve for Al-Cu, based on the peak hardening stress, shows a plateau rather like that for single crystals of pure copper. However, the plateau extends from 10^{-5} to 10^{-3} (plastic strain amplitude), i.e. displaced a decade of strain lower than that of copper. This implied that the localized strains in precipitation hardened alloys are orders of magnitude greater than those in pure metals and in support of this we found that the lives of our Al-Cu

single crystals are two orders of magnitude lower than those of copper single crystals tested at the same strains.

Believing that the lower limit of the plateau should correspond to a fatigue limit, we stress-cycled specimens for large numbers of cycles at stresses lower than that of the plateau. We find that the slip remains fine and uniform in such specimens, that PSB's do not form, and that cyclic softening does not occur. However, the specimens were observed to fail eventually because we had left the extensometer attached so as to detect softening and the knife edges had sunk into the metal by cyclic creep. Cracks grew from these sites because the fatigue stress limit necessary to nucleate a crack is higher than that necessary to exceed the threshold stress intensity for growth of an "artificial" crack.

We also compared the cyclic stress-strain curve of polycrystalline Al-Cu at low strains with that for monocrystalline Al-Cu, by dividing the stresses and strains of the polycrystalline alloy by Taylor's factor. We have been pleased to find that the polycrystalline curve <u>also has a plateau roughly corresponding to that for the single crystals</u>, and the plateau occurs at an <u>identical</u> (corrected) stress. This is a very important result because it means that the results and implications of our studies on monocrystals can be carried over to commercial metals. The roles of 1) the back stresses acting on PSB's from adjoining grains, 2) the texture and grain size of the polycrystal and 3) Sach's factor considerations were also explored.

Using Al-Cu monocrystals, we completed studies of persistent slip band behavior by "Finney-type" interferometry (5); i.e., we

cycled a specimen to a desired point in its life, interrupted the test and removed the specimen from the machine, microscopically recorded the slip band structure, polished the specimen, subjected it to a quarter cycle of strain to reveal the current state of slip behavior (as opposed to the accumulated behavior), and then studied the slip localization by interferometry. One side of the specimens was not polished so that the accumulated slip band behavior could be compared with the current behavior. We thus proved that PSB's do not form until just before the peak and we gathered observations on slip behavior during softening. Strain localizations as high as 0.6 were recorded.

TEM observations of the Al-Cu alloy were completed; the PSB structures in specimens cycled to failure have been observed on two orthogonal sections. The dislocation structures have been revealed and the θ'' precipitates observed to survive the cycling. A ball-model experiment of θ'' behavior has been completed in conjunction with another project and has been useful in assessing the kinetics of disordering (4).

In the closing stages of the project, an attempt was made to apply the results of monocrystalline Al-Cu alloy to commerical alloys based on the Al-Zn-Mg system (including a pure ternary alloy and high purity and regular 7075-T651 alloys with various processing histories. These alloys were supplied by the Army (Courtesy of J. Waldman)) and also a Ni-based superalloy single crystal MAR-M-200. The results from the latter were too complex to be handled easily. However, cyclic response on the Al-Zn-Mg alloys were conducted down to very low strain amplitudes, hitherto unexplored, for comparing

behavior with that of Al-Zn-Mg alloy single crystals (GP zone structures) studied by Wilhelm (6). The main result was that the plateau in both Al-Zn-Mg and commerical 7075 was suppressed, in the former because the grain size was smaller than that of the Al-Cu alloy and in the latter because the constituent particles and dispersoids homogenized the strain and inhibited strain localization.

Furthermore, extensive tests on the effect of variable amplitude loading on cyclic response in Al-Cu alloy have been completed. Just as in pure metal, cyclic overloads which are sufficient to carry the material to the stress-strain regime above the plateau, cause the suppression of the plateau in subsequent cycling at low amplitudes. Consequently, the fatigue limit is reduced because regions of localized strain, once activated, can continue to undergo preferential slip at stresses too low to nucleate them.

3. References in Support of the Results Section

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J.K. Lee, S.P. Bhat, R. de la Veaux and C. Laird, "Mechanisms of Cyclic Softening in Precipitation Hardened Alloys - A Ball Model Approach and Tests at 78K", Int. J. Fracture 17, 121, 1981.

A.S. Cheng, J.C. Figueroa, C. Laird and J.K. Lee, Cyclic Deformation of Polycrystalline Pure Metals and of Precipitation Strengthened Alloys", Riso Symposium, Denmark, 1981, 405-416.

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J.K. Lee and C. Laird, as (d) "Part II - Dislocation Microstructures", Mat. Sci. Eng. 54, 53, 1982.

C. Laird, J.M Finney and D. Kuhlmann-Wilsdorf, "Dislocation Behavior in Fatigue, Part VI, Variation in the Localization of Strain in Persistent Slip Bands", Mat. Sci. Eng. 50, 127, 1981.

J.M. Finney and C. Laird, "The Development of Slip Offsets Within PSB's during a Single Fatigue Cycle", Mat. Sci. Eng. 54, 137, 1982.

J.K. Lee and C. Laird, "Strain Localization during Fatigue of Precipitation Hardened Aluminum Alloys", Phil. Mag. 1982, in press.

The following publications remain under preparation at the time of filing this report:

A. Renard, A.S. Cheng, R. de la Veaux and C. Laird, "The Cyclic Stress-Strain Response of Polycrystalline Al-Zn-Mg Alloy and Commerical Alloys Based on this System".

S. Horibe, J.K. Lee and C. Laird, "Effect of Hold Time on The Cyclic Response of Al-4w/oCu Alloy Containing θ" Precipitates".

S. Horibe and C. Laird, "The Existence of Plateaus in the Cyclic Stress-Strain Curves of Polycrystalline Al-Cu Alloys".

S. Horibe and C. Laird, "Orientation Dependence and History Dependence of the Cyclic Response of Al-Cu Monocrystals, Part I, Containing θ" Precipitates, Part II, Containing θ' Precipitates".

5. List of Participating Scientific Personnel.

J. K. Lee, Graduate Student, Awarded Ph.D. degree.

A. Renard, Graduate Student, Awarded M.Sc. degree.

Dr. S. Horibe, Post-doctoral Student.

Informal cooperation with J. M. Finney and D. Kuhlmann-Wilsdorf.

C. Laird, Professor, Principal Investigator.